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FRICTION AND CONTACT RESISTANCE DURING SLIDING IN VACUUM OF SOME LOW-RESISTIVITY METALS LUBRICATED WITH SPUTTERED MOLYBDENUM DISULFIDE FILMS

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ABSTRACT

Thin films of MoS_2 were applied by direct-current sputtering to copper, silver, and beryllium disk specimens and to copper disk specimens ion plated with gold, rhodium, or palladium. Low-speed sliding friction tests in ultrahigh vacuum showed that adherent, low-friction $(0.01 < f < 0.1)$ films were obtained on all specimens except OFHC copper. However, the average dynamic contact resistance was high $(> 1$ ohm$)$ for all specimens except silver. High resistance peaks were a feature of all specimens throughout the duration of all tests.

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SUMMARY

The technique of direct-current sputtering was used to apply thin films of molybdenum disulfide (MoS_2) to copper, silver, and beryllium disk specimens and to copper disk specimens ion plated with gold, rhodium, or palladium. Ultrahigh vacuum sliding friction tests were conducted with a 4.75-millimeter-radius hemisphere (rider) running against the flat surface of a disk at 132 millimeters per minute. The tests showed that adherent, low-friction ($0.01 < f < 0.1$) films were obtained on all disk specimens except copper. The great majority of the MoS_2 films on the copper disks blistered and peeled during the sputtering process despite many changes in the presputtering cleaning procedure. Only one nonreproducible continuous film was obtained on a copper disk. It failed immediately by spalling from the surface during a vacuum friction test. All remaining materials combinations completed a 2-hour sliding friction test with no evidence of gross film failure. Although the coefficients of friction were low, the contact resistances were quite high (> 1 ohm) for all materials combinations except silver against MoS_2 on silver (0.015 ohm). In addition, contact resistance peaks were quite high ($>$ five times the average resistance) for all material combinations except gold against MoS_2 on gold (three times the average resistance).

INTRODUCTION

Recently, thin solid lubricant films of molybdenum disulfide (MoS_2) have been applied to two base materials (a nickel-chromium alloy and niobium) by a sputtering technique (ref. 1). The experimental results showed that the sputtered films of MoS_2 provided a low coefficient of friction ($0.06 < f < 0.09$) for many hours in a vacuum of

10^{-11} torr. Considering the thinness of these films (about 2500 Å or 2.5×10^{-7} m), their endurance is very good.

In view of these good initial results, sputtered films of MoS_2 were checked to see whether they would also provide effective lubrication of other metals in a vacuum environment, particularly those metals generally used for electrical contact applications. In such applications, the thinness of these MoS_2 films might be advantageous.

Molybdenum disulfide is widely used as an electrical contact lubricant in vacuum because it provides a very low coefficient of friction and low wear (refs. 2 to 6), although its electrical resistivity is high (850 ohm-cm, ref. 7). Molybdenum disulfide is generally incorporated into a brush material (e.g., MoS_2 and silver) which runs against slipring materials that have a low electrical resistivity (e.g., copper, silver, and gold). Lubrication is provided by the continuous release of the MoS_2 as the brush material wears. Low contact resistance is provided by the silver component in the brush material.

Sputtered thin films of MoS_2 on slipring surfaces might offer an alternate approach to the MoS_2 lubrication of sliprings in vacuum. As the thickness of a film decreases, the resistance across the film also decreases (ref. 8). Thus, sputtered thin films of MoS_2 might be useful as electrical contact lubricants if thin, adherent, long-lived lubricating films of MoS_2 can be obtained on the surfaces of materials generally used for electrical contact applications.

The objective of the investigation reported herein was to evaluate the kinetic coefficient of friction and the values of the dynamic electrical contact resistance for some selected electrical slipring materials lubricated with a thin film of MoS_2 applied to their surfaces by the technique of sputtering.

The experiments were performed with a 4.75-millimeter-radius hemispherically tipped rod (the rider or brush) sliding on the dry, flat surface of a 50.8-millimeter-outside diameter disk at a sliding speed of 132 millimeters per minute (1 rpm) in a vacuum of 10^{-11} torr. The sputtered MoS_2 films were applied to the disk specimens. The load used for all experiments was 100 grams, and the duration of each run was 2 hours, or less if failure of the lubricant film was apparent.

Specimen Materials

The specimen materials chosen for these experiments and the way they were used is shown in table I. The materials that were mated in each experiment are also listed in table I.

The metals gold, rhodium, and palladium were used as thin films that were ion plated onto OFHC (oxygen-free high-conductivity) copper disk specimens (refs. 9 and 10). This method was chosen because of the high cost of fabricating entire disk specimens

2

TABLE I. – MATING DISK SPECIMEN AND HEMISPHERICAL SPECIMEN MATERIALS

Disk specimen material	Hemispherical specimen materials (all bulk materials)
Bulk materials	
Copper, commercial OFHC	Copper, commercial OFHC
Silver, 99.99 percent purity	Silver, 99.99 percent purity
Beryllium, I-400 instrument grade	Beryllium, I-400 instrument grade
Ion-plated films	
Gold, 99.99 percent purity; ion plated onto OFHC copper base	Gold, 99.99 percent purity
Rhodium, 99.99 percent purity; ion plated onto OFHC copper base	Rhodium, 99.99 percent purity
Palladium, 99.99 percent purity; ion onto OFHC copper base	Palladium, 99.99 percent purity

from these expensive metals. However, the mating gold, rhodium, and palladium riders were fabricated wholly from these materials.

Specimen Preparation

The copper, beryllium, and silver disk specimens and all riders were initially machined to an 8 rms finish. Prior to use, the disk specimens were mechanically polished by using standard metallurgical polishing procedures. After polishing (or in some cases, after high-temperature vacuum outgassing), the disk specimens were coated on one face with a thin film of MoS_2 by use of the sputtering technique and apparatus described in reference 1.

The metals gold, rhodium, and palladium were ion plated onto OFHC copper disks by using the apparatus and techniques described in reference 9. All materials were ion plated under the same conditions to achieve approximately the same film thickness for each material. After ion plating, these specimens were also sputtered with a film of MoS_2. All materials were sputtered under the same conditions to achieve about the same film thickness of MoS_2 (~2500 Å or 2.5×10^{-7} m) on each disk. All films were applied to the disk specimens only.

APPARATUS

Ultrahigh Vacuum Chamber and Drive Mechanism

The ultrahigh vacuum chamber, in which the friction and contact resistance measurements were made, has been fully described in references 1 and 11. The disk

specimen was rotated by a tachometer-stabilized, variable-speed, direct-current electric motor coupled to a 900:1 ratio gearbox. Torque was transmitted through the vacuum chamber wall by two 20-pole circular permanent magnets positioned on opposite sides of a thin stainless-steel diaphragm welded to one of the large vacuum flanges. The magnet external to the vacuum chamber was mounted on the output shaft of the gearbox. The second magnet, inside the vacuum chamber, was mounted on the end of the shaft opposite the disk specimen.

Contact Resistance Measurement

A commercial four-terminal alternating-current milliohmmeter having full-scale ranges from 0.001 to 1000 ohms was used to measure the contact resistance. The electrical connections to the specimens are shown in figure 1. One current and one voltage lead from the ohmmeter are connected separately to opposite sides of a copper cup containing liquid gallium. The disk specimen is mounted on one end of an OFHC copper spindle. The spindle is mounted on the shaft by insulating glass-mica bushings and is secured with a locknut. A ring machined into the remaining end of the copper spindle and partially immersed in the gallium completes the electrical circuit to the disk specimen. The remaining current and voltage leads are connected directly to the electrically insulated rider. The output of the milliohmmeter is connected to a multichannel light-beam recorder.
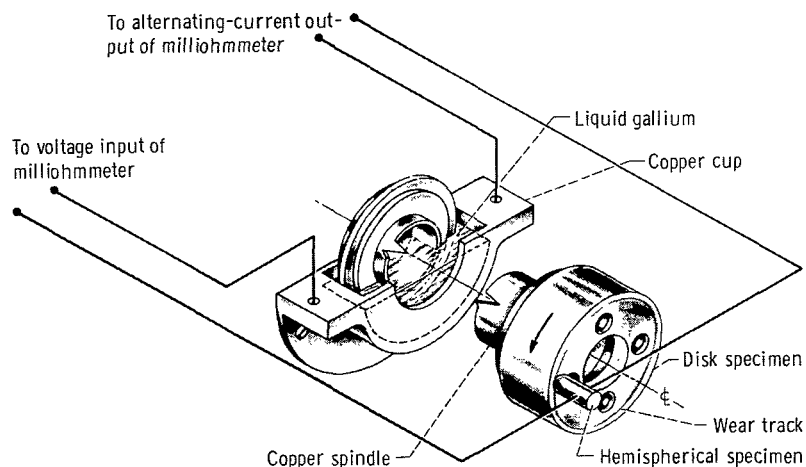
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Figure 1. - Contact resistance measuring circuit.

Frictional Force Measurement

A diagram of the frictional force measuring system is shown in figure 2. The insulated block in which the rider is mounted is affixed to the free end of a small cantilever beam. The frictional force developed between the disk and rider will bend the beam. The amount of beam displacement, which is proportional to the frictional force, is sensed by a capacitance probe mounted normal to the direction of bending. The output of the probe control is connected to a light-beam recorder channel calibrated in grams force.
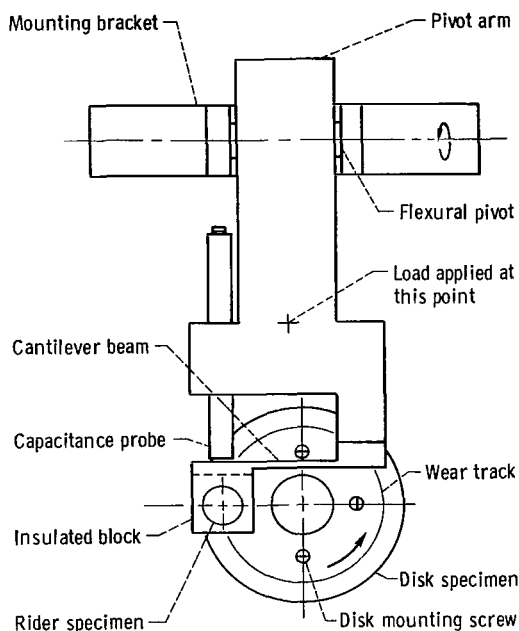
Mounting bracket — — Pivot arm

— Flexural pivot

— Load applied at this point

Cantilever beam —

Capacitance probe —

— Wear track

Insulated block —

— Disk specimen

Rider specimen — — Disk mounting screw

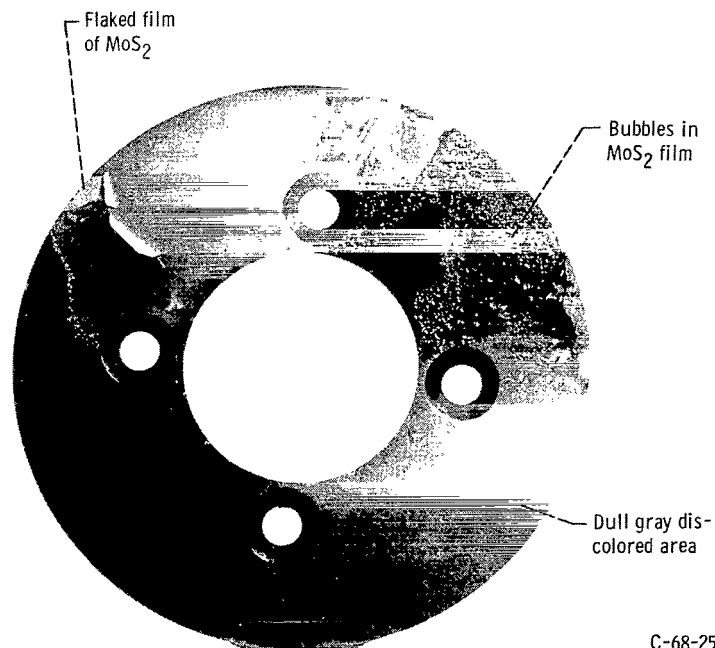Figure 2. - Frictional force measurement assembly.

RESULTS AND DISCUSSION

Sputtered Molybdenum Disulfide Films on Oxygen-Free

High-Conductivity Copper Disk Specimens

A smooth continuous film of MoS_2 was extremely difficult to obtain on the OFHC copper disk specimens. This fact is evidenced by figure 3, which shows the results generally obtained in attempts to sputter a film of MoS_2 on two OFHC copper disk

Flaked film of MoS$_2$
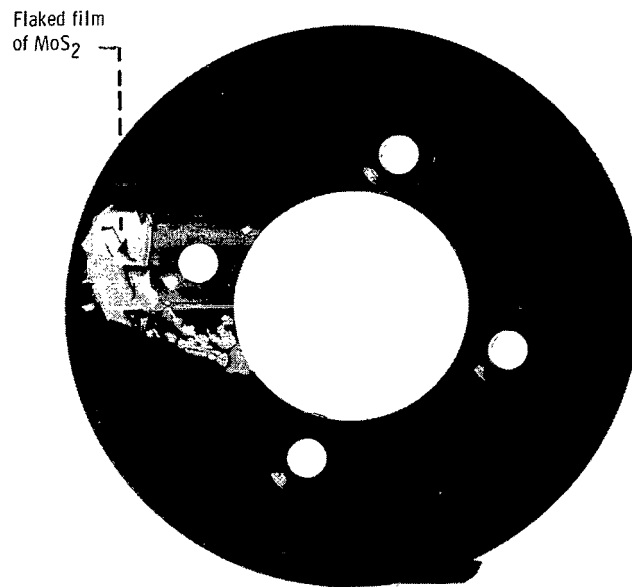
(a) OFHC copper disk specimen showing flaking of MoS$_2$ film.

Flaked film of MoS$_2$

Bubbles in MoS$_2$ film

Dull gray dis-colored area

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(b) OFHC copper disk specimen showing flaking and bubbling of MoS$_2$ film.

Figure 3. – Sputtered films of MoS$_2$ on two OFHC copper disk specimens.

specimens. Figure 3(a) shows the more common result, a flaking or peeling of the film from the copper surface.

Observations during the sputtering process revealed that, initially, the film was smooth and continuous and that the flaking or blistering occurred during the latter part of the sputtering process. Since these effects are generally indicative of the expansion of trapped gases beneath a deposited surface film, they were thought to be a result of the outgassing of the copper disk specimen as it was being heated during the sputtering process. Other OFHC copper disk specimens were outgassed in vacuum (10^{-6} torr) by heating to 430° C with an electron gun prior to sputtering with a film of MoS_2, but these films also blistered and peeled during the sputtering process.

Other variations in the cleaning procedure were tried, including the polishing of one disk specimen with 600 grit silicon carbide paper and then outgassing this specimen by heating in vacuum prior to sputtering with MoS_2. A continuous blister-free film was obtained on this specimen. However, when this film was subjected to an ultrahigh vacuum sliding friction test, using OFHC copper as the mating surface, the film failed immediately as evidenced by (1) a coefficient of friction of 0.5 to 0.6, and (2) a very low contact resistance reading that is indicative of metal-to-metal contact. A photomicrograph of a portion of the wear track on this specimen is shown in figure 4. Although the specimen completed slightly more than five revolutions, the appearance of copper in the wear track is very clear. The same photomicrograph also shows that much of the film in the wear
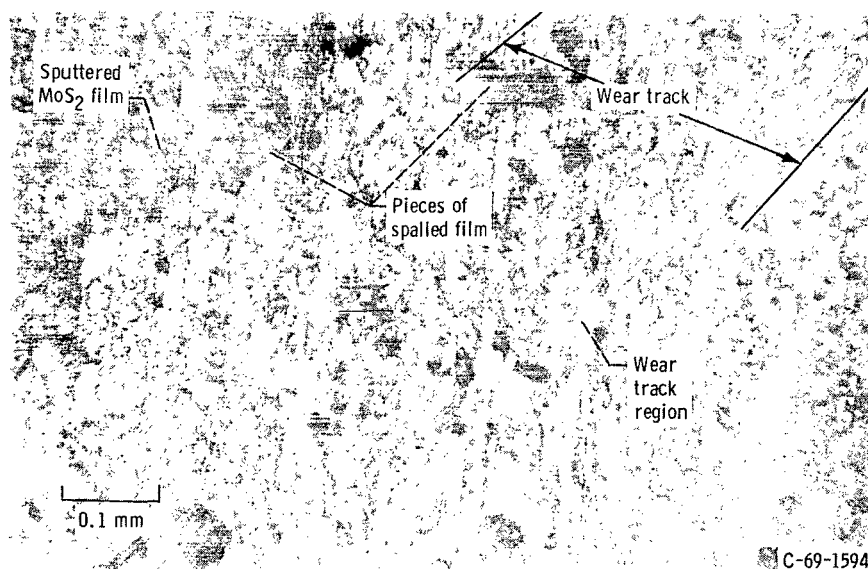

Figure 4. - Enlarged view of wear track on copper disk specimen sputtered with MoS_2. Run time, 2 hours; load, 100 grams; speed, 132 millimeters per minute (1 rpm); vacuum, 10^{-11} torr; surface finished with 600 grit silicon carbide paper.

track is simply spalled from the surface, which indicates very poor adhesion. Furthermore, the adhesion on this particular specimen is poor despite the relatively rough surface (600 grit polish) which should aid adhesion. All further attempts to reproduce a film by using this cleaning procedure resulted in failure.

The limited amount of contact resistance data for the experiment where copper was run against MoS_2 on copper showed large transient peaks of high resistance (>5 ohms). These resistance peaks were undoubtedly caused by the passage of pieces of film material across the contact interface. The large amplitude of the resistance peaks are thought to be caused by the large differences in bulk resistivity (about 10^9 ohms) between copper and MoS_2. This will be discussed in the next section.

The possible influence of other changes in the specimen cleaning procedures was examined, but none successfully produced a continuous film of MoS_2 on a copper surface. The one continuous film that was obtained seemed to be a chance affair. On the basis of these results, two conclusions can be made: (1) continuous films of MoS_2 are extremely difficult to obtain on OFHC copper surfaces, and (2) a sputtered film of MoS_2 on copper (if it can be obtained) does not function successfully as a lubricant because of its extremely poor adherence to this metal.

Sputtered Molybdenum Disulfide on Silver Disk Specimen

In marked contrast to the extreme difficulty of obtaining a continuous film of MoS_2 on a copper disk specimen was the relative ease of obtaining a continuous film of MoS_2 on the silver disk specimen. This result was not influenced by the specimen cleaning procedure because the initial cleaning procedures for both copper and silver disk specimens were identical.

The silver disk specimen sputtered with a film of MoS_2 was run against a silver hemisphere in ultrahigh vacuum for 2 hours. The data show that this materials combination displayed a low average coefficient of friction (f ~ 0.1, see fig. 5(a) and table II) for the entire 2-hour run. When the run was terminated, the film was still providing effective lubrication. The data also show that the average contact resistance was moderately low (~ 0.016 ohm, see fig. 5(c) and table II) with occasional peaks to about 5 ohms. The contact resistance data also revealed a region of high peak resistances that remained in the same section of the disk throughout the entire run. This peculiar phenomenon was also displayed by all other materials combinations that were examined in these experiments and was probably a function of the sputtering geometry.

The coefficient of friction and contact resistance data for one particular revolution (revolution 30) in the experiment where silver was run against MoS_2 on silver are shown in figure 6. The coefficient of friction decreases as the contact resistance increases. This behavior is believed to be caused by an increasing amount of MoS_2 in the
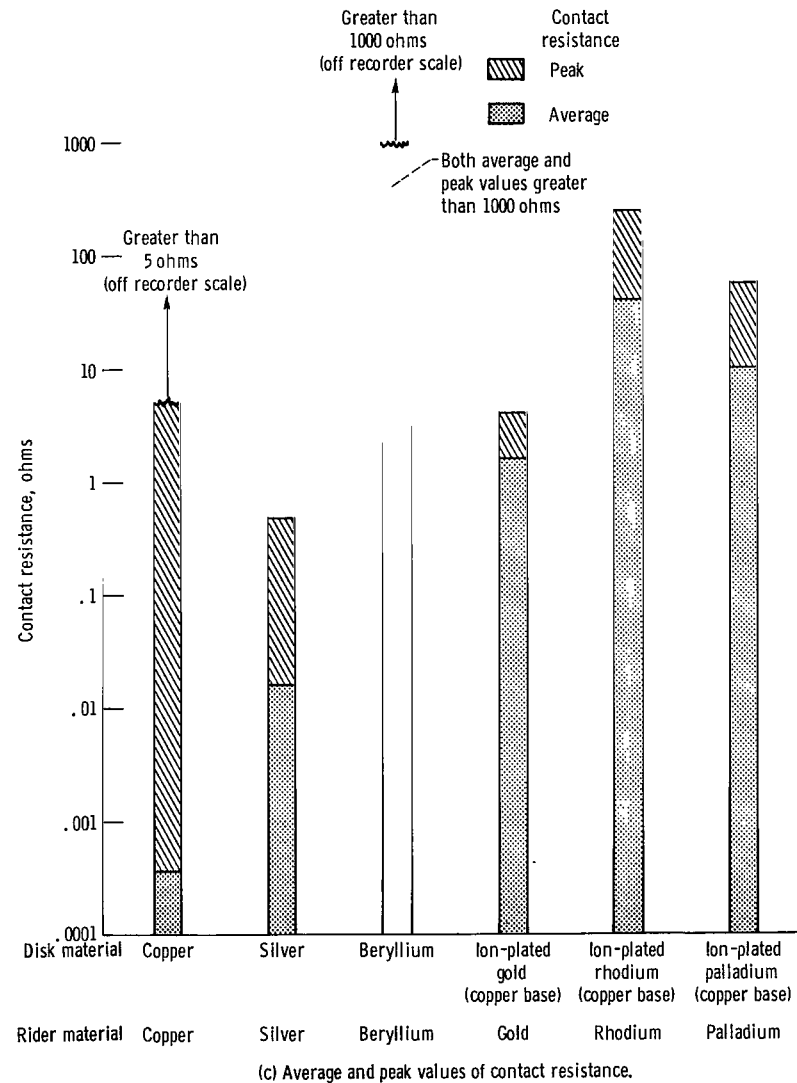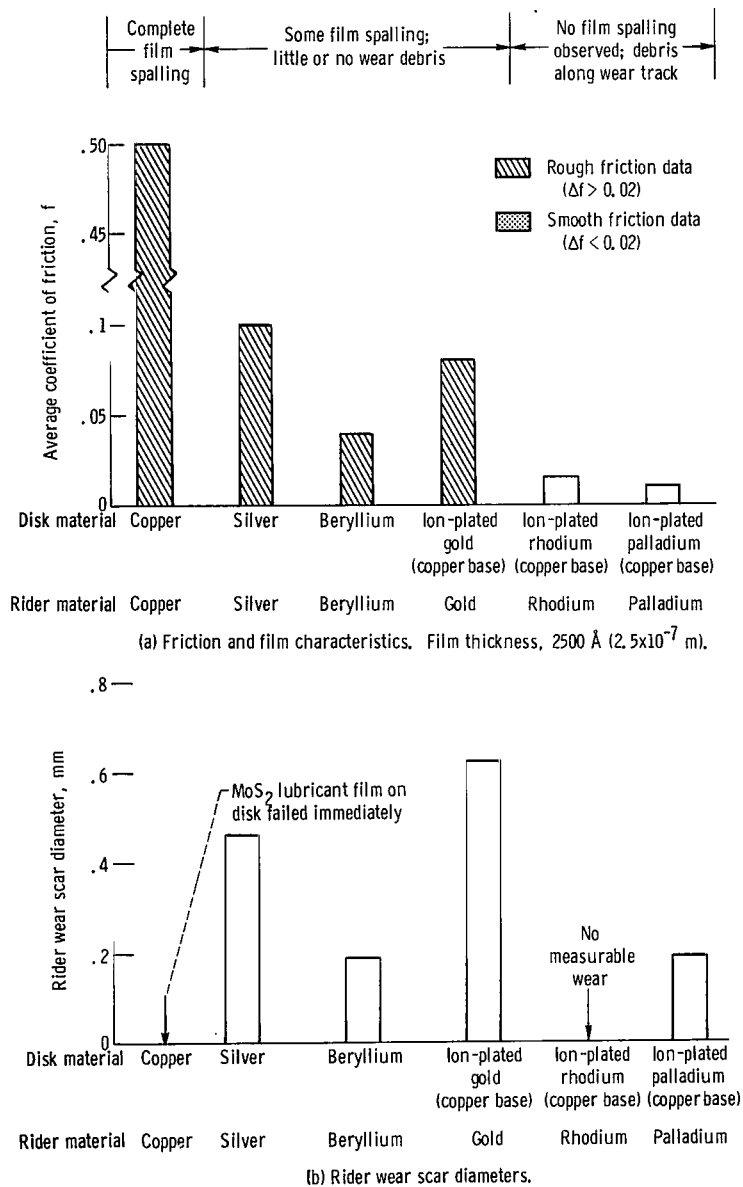
Complete film spalling | Some film spalling; little or no wear debris | No film spalling observed; debris along wear track

(a) Friction and film characteristics. Film thickness, 2500 Å (2.5x10^{-7} m).

(b) Rider wear scar diameters.

(c) Average and peak values of contact resistance.

Figure 5. - Experimental results for materials shown. Lubricant, sputtered film of MoS$_2$ on disk; film thickness, 2500 Å (2.5x10^{-7} m); load, 100 grams; sliding speed, 132 millimeters per minute (1 rpm); vacuum, 10^{-11} torr; duration of each run, 2 hours.

TABLE II. - SUMMARY OF RESULTS OBTAINED WITH SPUTTERED MOLYBDENUM DISULFIDE FILMS AS LUBRICANTS ON MATERIALS SHOWN

[Data obtained with a 100-g load at a sliding speed of 132 mm/min in vacuum of 10^{-11} torr; duration of each run, 2 hr.]

Sliding couple		Disk surface finish	Additional presputtering treatment	Average coefficient of friction	Rider wear scar diameter, mm	Contact resistance ratio, peak, ohms / average, ohms	Remarks
Rider	Disk						
-------------------	OFHC copper with sputtered film of MoS$_2$	Alumina polish	None	---------	--------	-------------	Part of MoS$_2$ coating peeled off during sputtering procedure
-------------------	OFHC copper with sputtered film of MoS$_2$	Alumina polish	Disk outgassed in vacuum at 700 K for 2 hours	---------	--------	-------------	Part of MoS$_2$ coating peeled off during sputtering procedure
Copper (OFHC)	OFHC copper with sputtered film of MoS$_2$	600 Grit silicon carbide polish	Disk outgassed in vacuum at 700 K for 2 hours	0.5	--------	$\dfrac{>5}{0.00035}$	Coating appeared good but failed immediately in vacuum sliding test; coating spalled, poor adherence[a]
Silver, 99.99 percent purity	99.99-Percent purity silver with sputtered film of MoS$_2$	Tin oxide polish	Disk outgassed in vacuum at 825 K for 2 hours; surface etched	0.1	0.46	$\dfrac{0.49}{0.016}$	Coating appeared good, ran successfully in vacuum sliding test for 2 hours;[b] contact resistance high in one sector
Beryllium, I-400 instrument grade	I-400 grade beryllium with sputtered film of MoS$_2$	Alumina polish	None	0.04	0.19	$\dfrac{>1000}{>1000}$	Coating appeared good; ran successfully in vacuum sliding test for 2 hours;[b] contact resistance very high in one sector
Gold, 99.99 percent purity	OFHC copper ion plated with gold then sputtered with MoS$_2$	Alumina polish prior to ion plating	OFHC copper disk outgassed in vacuum at 600 K for 6 hours	0.08	0.62	$\dfrac{4}{1.6}$	MoS$_2$ coating appeared good; ran successfully in vacuum sliding test for 2 hours;[b] contact resistance moderately high in one sector
Rhodium, 99.99 percent purity	OFHC copper ion plated with rhodium then sputtered with MoS$_2$	Alumina polish prior to ion plating	None	0.015	No measurable wear	$\dfrac{230}{40}$	MoS$_2$ coating appeared good; ran successfully in vacuum sliding test for 2 hours, contact resistance very irregular; friction data fairly smooth
Palladium, 99.99 percent purity	OFHC copper ion plated with palladium then sputtered with MoS$_2$	Alumina polish prior to ion plating	None	0.01	0.19	$\dfrac{55}{10}$	MoS$_2$ coating appeared good; ran successfully in vacuum sliding test for 2 hours;[b] friction data very smooth

[a]Continuous coating not reproducible.
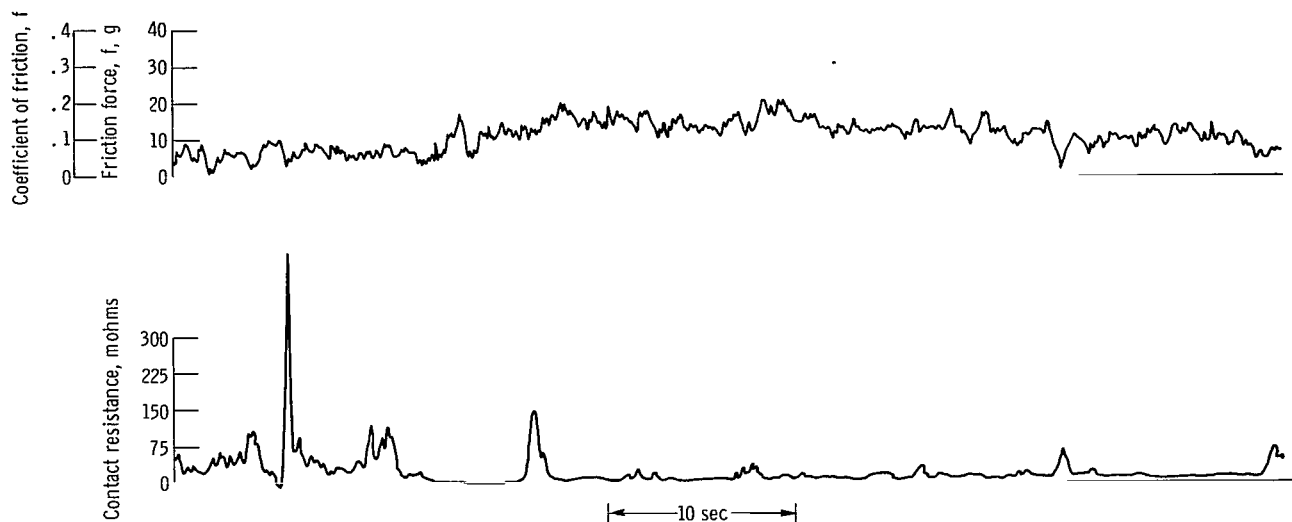
[b]Coating had not failed when run was terminated.

Figure 6. – Friction force and contact resistance against time for silver disk specimen sputtered with MoS$_2$ running against silver hemisphere. Load, 100 grams; speed, 132 millimeters per minute (1 rpm); vacuum, 10^{-11} torr; revolution 30.
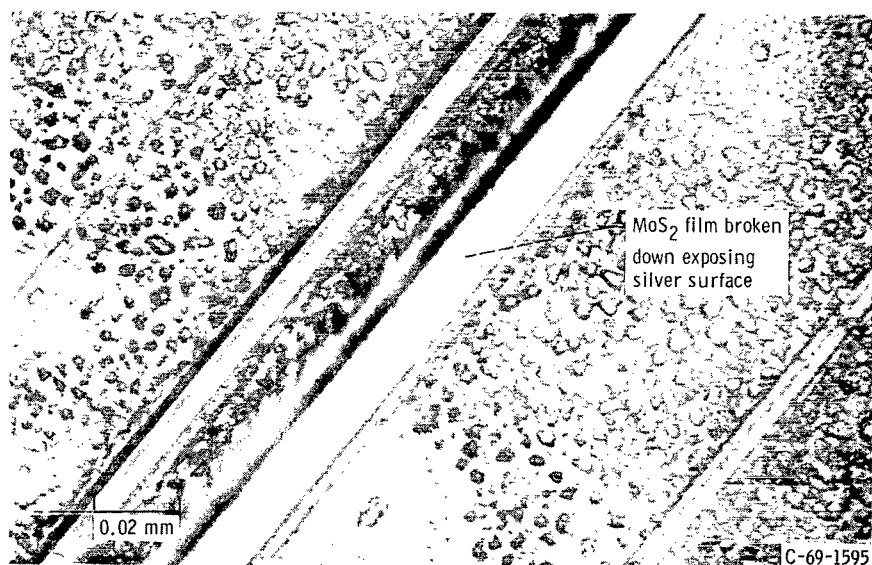

Figure 7. – Enlarged view of wear track on silver disk specimen sputtered with MoS$_2$. Run time, 2 hours; load, 100 grams; speed 132 millimeters per minute (1 rpm); vacuum, 10^{-11} torr.

contact region. If this is true, then conversely, when the contact resistance decreases, the contact region must be becoming more metallic, and the coefficient of friction should rise. The data of figure 6 show that it does, although the increase is small. Thus, the larger variations in friction and contact resistance, as the disk rotates, must be due to a continuous variation in the composition of the contact area. A photomicrograph (fig. 7) of a portion of the wear track on the silver disk sputtered with MoS_2, after a 2-hour run in ultrahigh vacuum, lends a bit more credibility to the proposed cause of the larger changes in friction and contact resistance. It can be seen that the sputtered film of MoS_2 has broken down along one edge of a portion of the wear track exposing the silver base material. Also, the exposed silver does not occupy all the wear track, only varying portions of it. It is easy to see, then, how the composition of the contact area may change as the rider traverses this region.

This rather large area of exposed silver base material in the wear track is also believed to be responsible for this combination of materials having the lowest contact resistance of all materials successfully completing the 2-hour vacuum sliding friction test. The small differences in the bulk resistivities of the metals used would not account for the very large difference in the contact resistance data among the metals.

The contact resistance is much more sensitive to the composition of the contact region than the coefficient of friction, especially if the bulk resistivity of the lubricant film is much larger than the bulk resistivity of the base material ($R_{film} \gg R_{base}$). In the case of MoS_2 and silver, the ratio of R_{film}/R_{base} is approximately 10^9. The ratio of the coefficients of friction for these same materials would be f_{film}/f_{base} of about 10^2 (assuming for MoS_2 lubrication $f \sim 0.01$ and for a silver-silver contact $f \sim 1$). This large difference in ratios could account for the fact that the amount of metal-to-metal contact encountered in the combination silver against MoS_2 on silver is insufficient to exert a large influence on the measured coefficient of friction. However, the same amount of metal-to-metal contact would be sufficient to exert a very large influence on the contact resistance because of the much larger ratio of R_{film}/R_{base}. Thus, the large peaks in the contact resistance data must represent a predominance of MoS_2 in the contact area. This explanation would also support our earlier hypothesis concerning the large contact resistance peaks in the earlier copper experiment, although little effect is noted in the coefficient of friction data. This same argument can be extended to all materials combinations where R_{film}/R_{base} is large and some metal-to-metal contact occurs because of film breakdown.

The amount of wear on the silver rider (measured as wear scar diameter and shown in fig. 5(b)) was the second largest of all materials examined in these experiments. The large amount of wear was undoubtedly the result of the inherent softness of pure silver. This property of silver might also offer an explanation for the breakdown in only one portion of the wear track on the pure silver disk. The amount of deformation of the

base material in this region was simply greater than the maximum amount the sputtered film could accommodate.

Sputtered Molybdenum Disulfide on Beryllium Disk Specimen

No problems were encountered in obtaining an adherent, sputtered film of MoS_2 on the beryllium disk specimen. A sliding friction test on this specimen running against a beryllium rider in vacuum showed an average coefficient of friction of about 0.04 for the entire 2-hour run. The data showed no evidence of impending film failure when the run was terminated. The contact resistance data for this materials combination showed peak contact resistances of greater than 1000 ohms, the highest for any of the materials combinations examined. (Separate measurements showed peak resistances to be about 5000 ohms.) The contact resistance data also revealed that the contact resistance remained in excess of 1000 ohms for approximately one-half revolution of the disk, whereas the remainder of the disk showed an average contact resistance of about 250 ohms. No large differences in the coefficient of friction were observed as the contact resistance made the rather sharp transition from 250 to greater than 1000 ohms. The coefficient of friction was, however, slightly lower in the high contact resistance region.

Microscopic examination of the disk revealed MoS_2 film spalling alongside the wear track. The spalling was not as complete as that on the copper disk but seemed to be
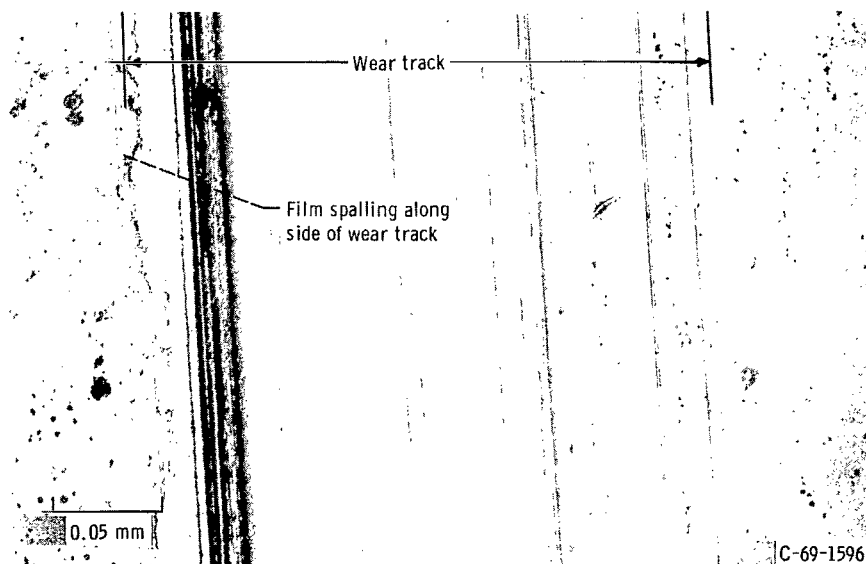

Figure 8. - Enlarged view of wear track on beryllium disk specimen sputtered with MoS_2. Run time, 2 hours; load, 100 grams; speed, 132 millimeters per minute (1 rpm); vacuum, 10^{-11} torr.

more than that on the silver disk. A photomicrograph of a portion of the wear track on the beryllium disk is shown in figure 8. A close examination of the wear track itself showed that the characteristic color of sputtered MoS_2 was almost totally absent in the wear track, which suggested that much metal-to-metal contact was occurring. The contact resistance and coefficient of friction data do not support this observation, however, because the contact resistance is much too high (~ 250 ohms) and the coefficient of friction is much too low (0.04) for a beryllium metal-to-metal contact. The coefficient of friction seems to support MoS_2 lubrication, but the contact resistance is too high to indicate the presence of MoS_2 alone unless it is fairly thick. Data are insufficient at this point to support any conclusions regarding the unusual performance of this materials combination.

Although the high contact resistance of this materials combination would preclude its use for electrical contact operation, the sputtered film of MoS_2 would be an effective lubricant for beryllium in purely mechanical applications.

Sputtered Films of Molybdenum Disulfide on Oxygen-Free High-Conductivity Copper Disk Specimens Ion Plated with Gold, Rhodium, or Palladium

The major difference between the ion-plated thin-film materials and the specimen materials used in bulk form is that the mechanical properties of the thin films will differ significantly from the mechanical properties of these same materials in bulk form. The base material for the ion-plated films (OFHC copper) would exert an overwhelming influence on the mechanical properties of these thin films, particularly with regard to deformation. In addition, the surface chemistry of the specimens is no longer that of copper but is that of the film material. The influence of these ion-plated films is evidenced by comparing the endurance life of a sputtered film of MoS_2 on copper to that of MoS_2 on copper ion plated with rhodium, gold, or palladium. The difference is very marked.

Sputtered films of MoS_2 were easily obtained on all ion-plated specimens with no evidence of blistering or peeling during the sputtering process. Figure 9 shows sputtered films of MoS_2 on the ion-plated rhodium and ion-plated palladium specimens. Compare the appearance of these films with those obtained on copper (fig. 3, p. 6). The resulting coefficients of friction in ultrahigh vacuum for these materials systems are shown in figure 5(a) and table II (pp. 9 and 10). The average coefficient of friction for palladium against MoS_2 on palladium (f ~ 0.01) was the lowest of all materials examined in these experiments. In addition, the friction force data for rhodium against MoS_2 on rhodium and palladium against MoS_2 on palladium were very smooth (low amplitude) in
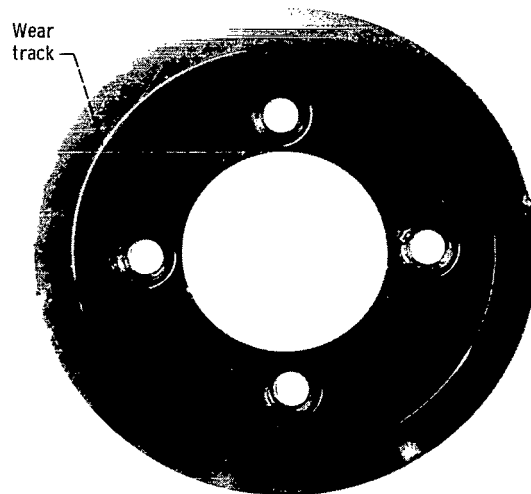
(a) Sputtered film of MoS_2 on OFHC copper disk specimen ion plated with rhodium.
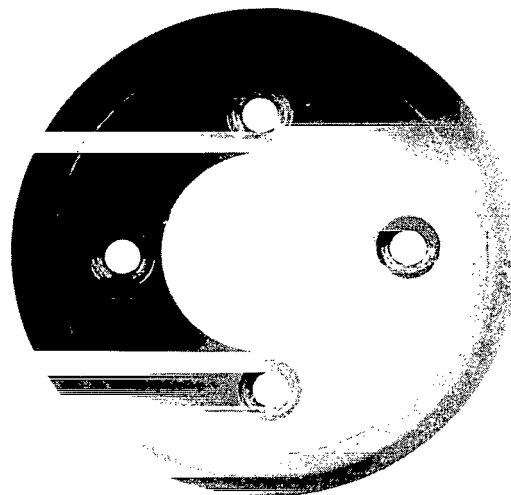
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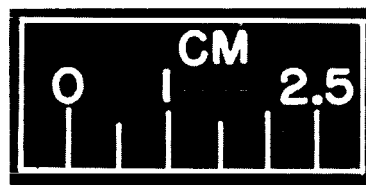
(b) Sputtered film of MoS_2 on OFHC copper disk specimen ion plated with palladium.

Figure 9. - Sputtered films of MoS_2 on ion-plated rhodium and ion-plated palladium disk specimens after 2-hour run in 10^{-11} torr vacuum with 100-gram load on rider specimen.
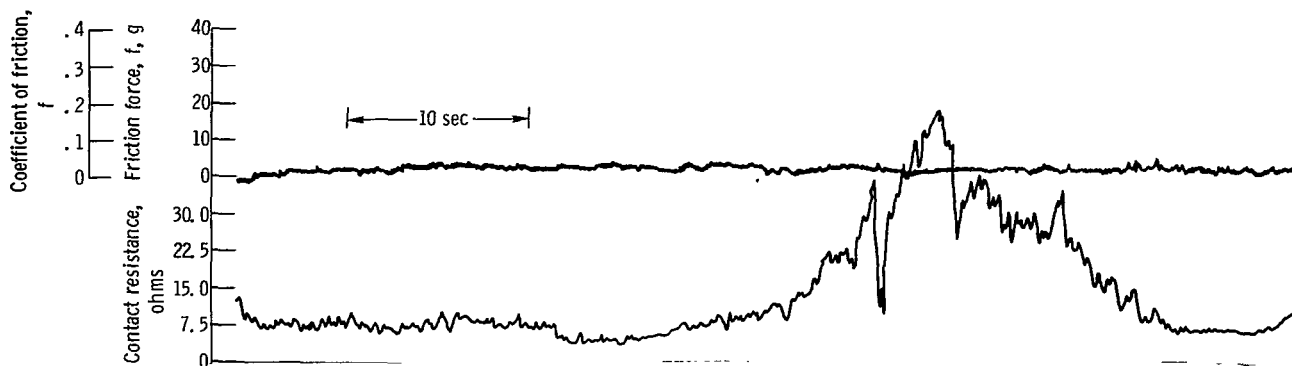
Figure 10. - Frictional force and contact resistance against time for OFHC copper base ion plated with palladium and sputtered with MoS_2. Load, 100 grams; speed, 132 millimeters per minute (1 rpm); vacuum, 10^{-11} torr; revolution 120.

comparison with the remaining materials. An example of the smooth low coefficient of friction is shown in figure 10, which shows some data for palladium against MoS_2 on palladium (revolution 120).

The sputtered films of MoS_2 provided very effective lubrication of all three ion-plated films for the entire 2-hour duration of each run. No evidence of impending film failure was suggested by the data when the runs were terminated.

The gold rider displayed the largest wear scar diameter of all materials examined, whereas no wear scar could be found on the rhodium rider even under a magnification of 500. The wear of the palladium rider was about equal to that of the beryllium rider. The wear scar diameters of these materials are shown in figure 5(b).

Although the lubricating qualities and adherence of the sputtered films of MoS_2 on the ion-plated films of gold, rhodium, and palladium were excellent, the average contact resistance of all these materials combinations was, again, quite high (fig. 5(c)). The lowest average contact resistance of the group was displayed by the gold against MoS_2 on gold, whereas the highest average contact resistance was displayed by the rhodium against MoS_2 on rhodium. The discussion of the experiments where silver was run against MoS_2 on silver suggests that, among the three-ion plated films examined, the greatest amount of metal-to-metal contact occurred in the gold system. Microscopic examination of the disk wear tracks on all three specimens showed this to be true. Some of the MoS_2 film had broken down in the wear track on the ion-plated gold specimen and exposed the gold surface (fig. 11). Film breakdown appeared much like that on the silver surface (spalling) except that it was much less extensive than on the silver. No visual evidence of film breakdown could be found in the wear tracks on either the rhodium or palladium specimens, although small scattered piles of powdery wear debris were ob-served alongside the wear tracks on both of these specimens. This is shown in figure 12 for the ion-plated rhodium specimen. The lack of film breakdown on the ion-plated rho-dium and palladium specimens might offer an explanation for their high contact resist-
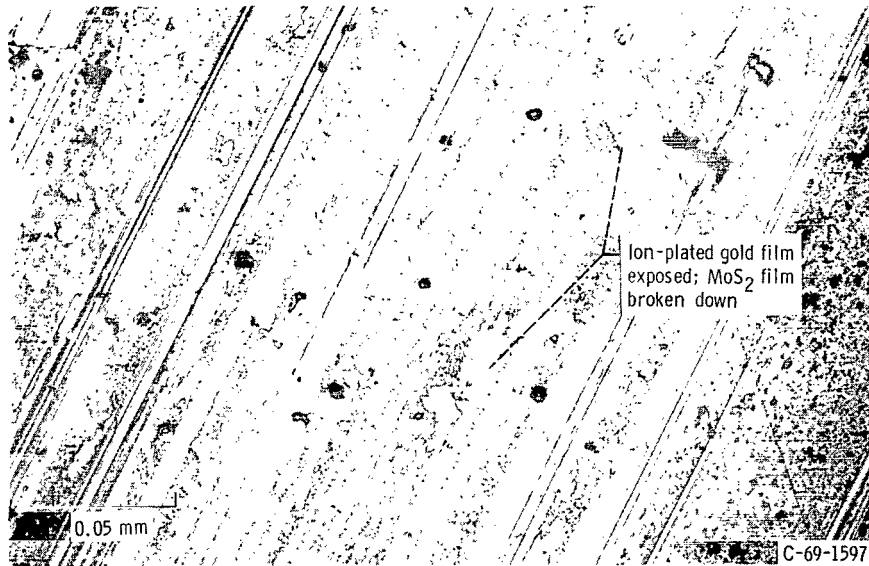
16

Figure 11. - Enlarged view of selected area of wear track showing MoS_2 film breakdown and exposure of ion-plated gold film. Run time, 2 hours; load, 100 grams; vacuum, 10^{-11} torr.
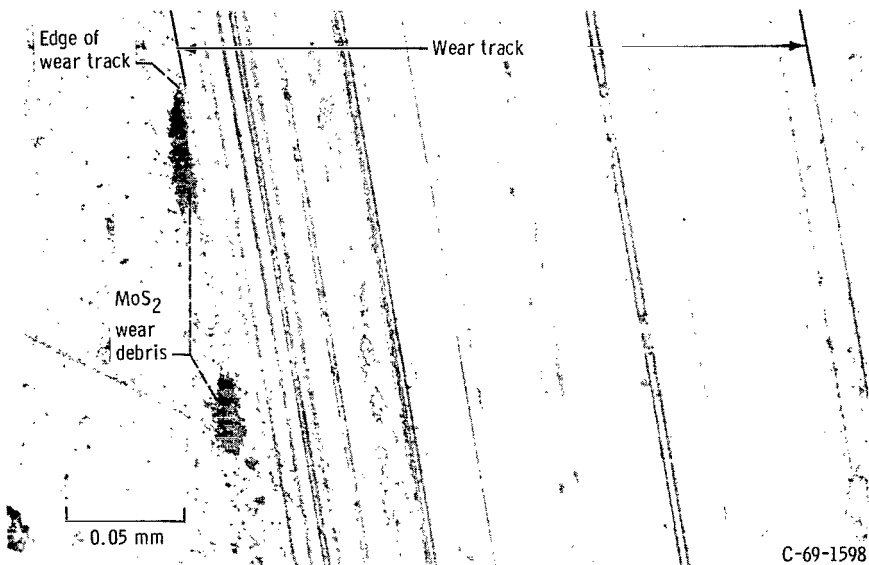

Figure 12. - Enlarged view of OFHC copper disk specimen ion plated with rhodium and then sputtered with MoS_2. Run time, 2 hours; load, 100 grams; speed, 132 millimeters per minute (1 rpm); vacuum, 10^{-11} torr.

17

ance. The fact that rhodium displayed the highest contact resistance in the group might possibly be attributed to its high hardness, which would result in a very small contact area.

Additional Discussion of Copper – Molybdenum Disulfide Results

The experimental results of the copper against MoS_2 on copper suggest some basic incompatibility between these two materials which affects film adherence. These results could be interpreted to mean that it might be very difficult to obtain a transfer film of MoS_2 on copper surfaces in sliding systems that use these materials (sliprings, gears, bearing cages, etc.). Since a transfer film is necessary for effective solid film lubrication, any difficulties in obtaining a transfer film would lead to poorer results.

Experiments using silver-MoS_2 electrical brushes running against copper sliprings have given poorer results than when the brushes were run against silver- or rhodium-plated silver sliprings, but no reasons were given for this behavior (ref. 4). The experimental results of the copper against MoS_2 on copper suggest that the reason for the poorer results might be the difficulties in obtaining a transfer film of MoS_2 from the silver-MoS_2 brushes to the copper surface of the sliprings. In addition, other experiments have shown that some improvement in performance results by plating copper sliprings with rhodium where graphite-MoS_2 brushes are used (ref. 12). The results of the sputtered MoS_2 experiments also suggest a reason for this improvement. The MoS_2 develops a much better transfer film on the rhodium surface than on the copper surface.

The behavior of sputtered films of MoS_2 on copper implies that it might be well to avoid MoS_2 lubrication of copper parts. However, in certain situations, copper might be the only material suitable for a particular job because of its high electrical and thermal conductivity coupled with its relatively low cost. In this case, lubrication with MoS_2 can be successful if the copper part is first plated with rhodium or palladium, as these experiments show. This approach would result in an economical copper part that is more compatible with MoS_2 lubricated systems.

Recently, small amounts of copper have been added to the silver-MoS_2 composites that are used as electrical brushes (ref. 3). The addition of copper hardened the silver, thereby reducing brush wear. The adverse results obtained with the sputtered films of MoS_2 on copper suggest that copper may not be the best choice for hardening silver in a MoS_2-lubricated system. A much better choice would seem to be palladium, which has about the same effect on the hardness and electrical resistivity of silver as copper, although it is somewhat more expensive (ref. 13). The experimental results obtained in the experiments on sputtered films of MoS_2 indicate that palladium was more effectively lubricated with MoS_2 than with copper.

CONCLUDING REMARKS

Sputtered films of MoS_2 are not useful for the lubrication of copper surfaces. However, they can be successfully employed for the lubrication of silver, beryllium, gold, rhodium, or palladium surfaces. The data showed that these sputtered films of MoS_2 were effective lubricants for the selected materials, but because of the excessive and erratic contact resistance displayed by all materials combinations, the films of MoS_2 should be used only in mechanical applications. The possible exception is silver, which had an average contact resistance of 0.016 ohm. This low value of contact resistance was due to the extensive metal-to-metal contact which occurred in this combination of materials.

Improvements in the electrical performance of the sputtered films of MoS_2 might be obtained by sputtering silver (or some other suitable material) simultaneously with MoS_2.

SUMMARY OF RESULTS

From the investigation of the performance of sputtered films of molybdenum disulfide (MoS_2) as lubricants for some selected low-resistivity metals sliding against themselves in ultrahigh vacuum, the following results were obtained:

1. Continuous, adherent sputtered films of MoS_2 were obtained on all specimens except oxygen-free high-conductivity copper.

2. All successfully obtained films ran for 2 hours without failure in low-speed (132 mm/min) sliding friction tests in ultrahigh vacuum (10^{-11} torr). No evidence of impending film failure on any specimen (except copper) was suggested by the data when the run was terminated at the end of 2 hours.

3. The average coefficient of friction for the sputtered films of MoS_2 on the selected metals ranged from a high of 0.6 for the copper running against MoS_2 on copper to a low of 0.015 for palladium running against MoS_2 on palladium.

4. The contact resistance data showed relatively high peak values for all specimens. The highest peak value of 5000 ohms was shown by the beryllium running against MoS_2 on beryllium. The lowest peak value of 0.49 ohm was shown by the silver running against MoS_2 on silver.

5. The dynamic contact resistance data showed the contact resistance to be quite erratic throughout any given revolution for all specimens.

6. Microscopic examination of the wear tracks on the silver, beryllium, and ion-plated gold disk specimens revealed considerable MoS_2 film breakdown in the wear track with little or no wear debris in evidence.

7. Microscopic examination of the wear track on the ion-plated rhodium and ion-plated palladium disk specimens revealed that the MoS_2 film remained largely intact in the wear track with some piles of powdery wear debris alongside the wear track.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, April 28, 1969,
            129-03-13-09-22.

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